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TURBULENT BED COOLING TOWER

Ronald G. Barile

Purdue University

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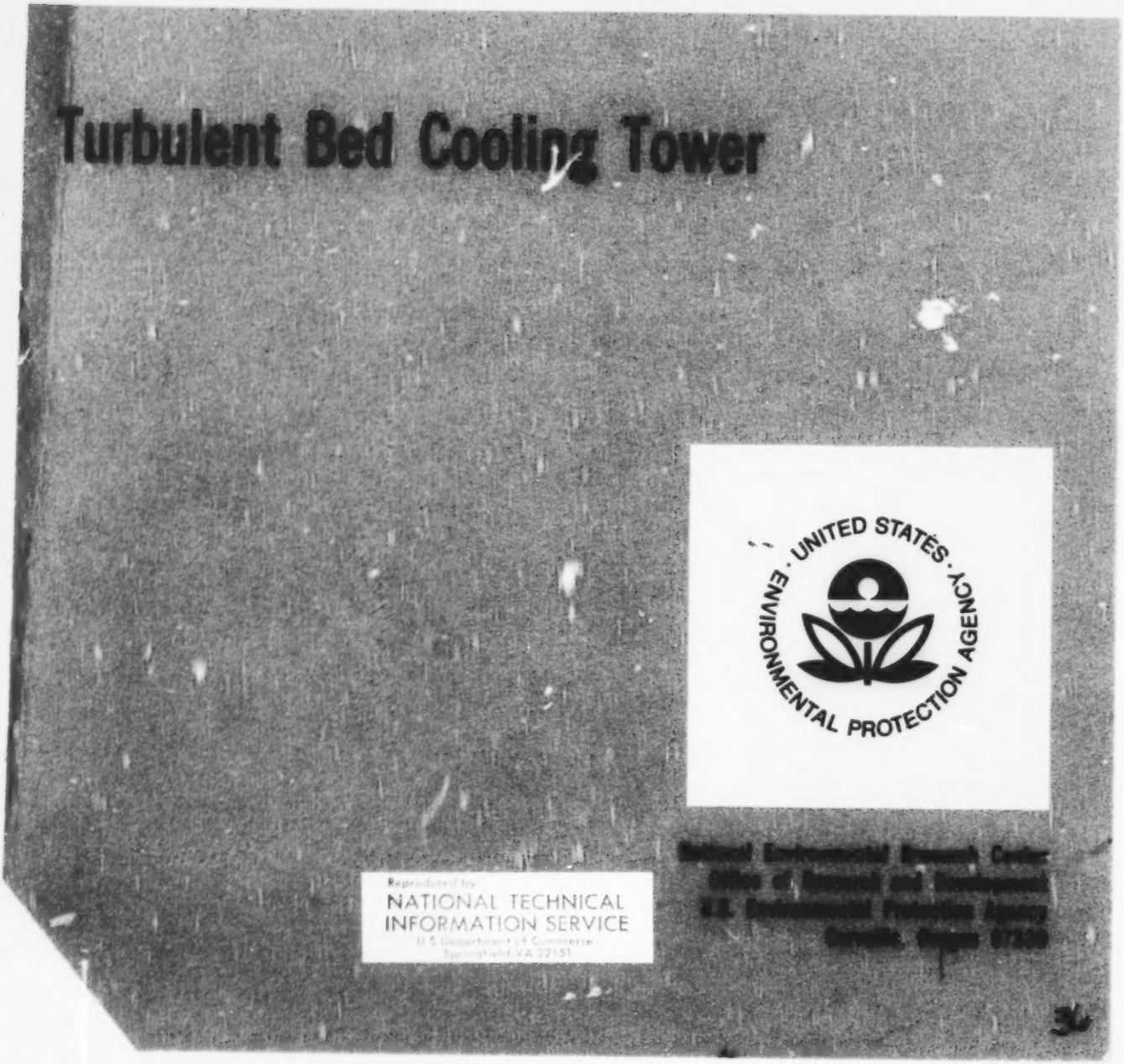

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TURBULENT BED COOLING TOWER

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SECTION I

CONCLUSIONS

1. The turbulent bed cooling tower (TBC) can accomplish water cooling ranges within about one foot of packing (10-15 ft tower) which normally require full-size mechanical draft towers, i.e., 30-50 feet high.

2. Comparison of the TBC with mechanical draft towers in terms of the tower characteristic shows that the TBC at its best is equivalent to conventional towers.

3. Comparison of the TBC with mechanical draft towers in terms of the power ratio, the ratio of total auxiliary water-and air-moving power to the cooling load, shows that conventional towers have about a factor of 1.5 to 2 advantage (lower power ratio) as compared to the TBC, but again, in some cases they are equivalent.

4. Compared to a mechanical draft tower in a given case:
   a. The TBC appears to require more air power (due to the requirement of fluidizing the spherical packing).
   b. The TBC would require lower water pumping head (due to the shorter tower required for a given range).
   c. The TBC would require less capital investment (due to the shorter tower, but similar basin area).

5. The TBC performance is close enough overall to conventional towers so that it should be investigated for further developments. It does provide an alternative cooling device with potentials equal to or superior to mechanical induced draft cooling tower.

6. The non-plugging characteristics of TBC allow its use for cooling cycles with waste or highly saline waters.

SECTION II

RECOMMENDATIONS

1. The key factor in improving the TBC is to reduce air pressure drop, and as a result power ratio and operating costs. This could be approached by:

    a. Enlarging the spherical packing
    b. Multiple staging of packing which would require less packing for a given cooling range.
    c. Other mobile packing innovations.

2. The TBC should be assessed in an optimization computer package for power-generation cooling which includes turbine, condenser, and cooling tower sizing as well as costing.

3. Economic evaluation of the TBC should be performed, especially capital requirements.

4. A scaled-up version of the TBC, say 3-10 ft in diameter, would be of great value in determining its potential to be a competitive cooling tower.

SECTION III
INTRODUCTION

SCOPE AND PURPOSE

This project was undertaken to show the feasibility of using the turbulent bed contactor (TBC) as a cooling tower for application to electric power generation. The scope included design, construction and testing of a pilot-scale TBC and a warm water loop representing the cooling water efflux from condensers in a power plant. Testing consisted of measuring air pressure drop, cooling performance, and limiting operating characteristics (e.g., flooding, slugging, etc.) for conditions typical of industrial cooling towers. The results were used in a preliminary analysis to specify operating conditions for the comparison of the TBC with existing industrial cooling towers especially the induced-draft, wet, cross-flow type.

GENERAL BACKGROUND

Turbulent bed contacting is a relatively new and highly effective means of contacting gas and liquid streams. The process is generally classified as three-phase, countercurrent flow. Operation in a vertical column consists of a process liquor being sprayed down through a bed where it contacts an upward flowing gas stream. The action of the two streams is responsible for fluidizing the low-density bed packing which is maintained in a highly turbulent state. This turbulence is responsible for intimate mixing of the two streams and for a high rate of transfer. Indeed, transfer coefficients two orders of magnitude greater than those of

conventional fixed bed operation have been reported.[1,2]

Most applications of the turbulent bed contactor (TBC) have been as absorbers or scrubbers. The non-plugging characteristic of this contactor makes it suitable in handling streams containing particulate matter, precipitates, algae, etc. Additionally, there is little tendency for channelling and bypassing. Other less typical uses, e.g., dehumidification of a hot, wet air stream, suggest the possibility of the cooling tower application.

Turbulent Bed Contactors

The first published account of a commercial turbulent bed contactor appeared in 1959 and explained its use as a scrubber to remove particulate matter from a dust laden gas.[3] H.R. Douglas et al.[1] made pilot studies of the absorption of CO_2 in an alkaline process liquor and SO_2 in NaOH and $Mg(OH)_2$ solutions. The striking result of their work was the large increase in flow rates possible and the increase of two orders of magnitude in the overall mass transfer coefficients both compared to conventional fixed bed towers. The authors attributed the increased transfer to intimate mixing caused by turbulence which minimized the large transfer resistance characteristic to packed towers. W.J.M. Douglas[2] studied the absorption of ammonia gas by water, and mass and heat transfer in the dehumidification of a hot, wet air stream. Liquid flow rates ranged from 2460 to 15,000 lb/hr-ft^2 and gas rates from 1037 to 2040 lb/hr-ft^2. The results indicated that dramatic reductions in tower size would be possible in certain interphase transport situations due to the high mass transfer rates observed. Experiments by Chen and Douglas delineated important TBC characteristics of holdup, minimum fluidizing velocity and liquid backmixing.[4] Further work by Douglas and coworkers has subsequently been reported in the areas of pressure drop,[5] bed expansion,[6] and hydrodynamic characteristics including a pressure drop correlation.[7]

Parallel studies on the turbulent bed appeared in the Russian literature concurrently. Several papers reported[8-11] on studies aimed at generalizing its characteristics and establishing design principles. Pressure drop, holdup, bed height, and flow regimes were considered. Much of the pressure-drop data were not applicable to the present topic because a low-free-area base plate was used (34.5%). Such a plate offered significant flow resistance, of the order of the bed itself, and resulted in excessive pressure drop due to liquid holdup and premature flooding. Pressure drop data were also measured with a new variation, i.e. with the use of disc packing.[11]

DESCRIPTION OF PHASES OF THE PROJECT

Initial results of the group at Purdue University were published in detail by Meyer[12] and later extended and summarized by Barile and Meyer[13]. Meyer's objective was to build the TBC system and take only representative pressure drop data. In this initial attempt at construction, flow circulation and flooding in the plenum area, where the air turned from horizontal to vertical, caused uncertainties in pressure drop and column flooding measurements. Carefully designed turning vanes fabricated from brass and an efficient downcomer plate added below the base plate solved these problems. More accurate pressure and flow data were then reported by Dengler[14] in his study of cooling performance. The latter was also extended and summarized by Barile, Dengler, and Hertwig.[15] Further comprehensive studies of pressure drop is the topic of a Master's thesis by Hertwig.[16] An overview of work reported in [12-16] is the subject of the present document.

THEORY OF COOLING TOWERS

In the development of the theory, heat and mass balances are made between the water and air streams and empirical rate equations are written for mass and heat transfer. Important simplifications result

in the development by introducing the Lewis relation and by using the enthalpy potential as a driving force for heat transfer. The following is a summary of the resulting equations as used here for data interpretation.

Equation (1) may be used to express cooling tower performance

$$C_p \int_{t_{L1}}^{t_{L2}} \frac{dt_L}{i_L - i_G} = \frac{KaV}{L} \qquad (1)$$

where t_{L2} and t_{L1} = inlet and outlet water temperatures, respectively, °F

i_L and i_G = the enthalpy of saturated air at the water temperature, and the enthalpy of the bulk air, respectively (BTU/lb-dry-air)

Ka = overall mass transfer coefficient (lb/hr-ft^3)

V = packing depth (ft)

L = liquid flux (lb/hr-ft^2)

C_p = Specific heat of water (Btu/lb-°F)

The term KaV/L is called "tower characteristic" by Lichtenstein[17] and is used to enumerate tower performance. Tower characteristic is a reflection of tower performance over a wide variety of possible conditions. Its value is usually independent of ambient conditions. The calculation of tower characteristic is made by numerical integration of the left side of Equation (1).

By making appropriate substitutions, expressions for the number of transfer units and height of a transfer unit may be found as follows:

$$\int_{i_{G1}}^{i_{G2}} \frac{di_G}{i_L - i_G} = \frac{KaV}{G} = \frac{KaV}{L} \cdot \frac{L}{G} = NTU \qquad (2)$$

$$\frac{V}{NTU} = \frac{G}{Ka} = HTU \qquad (3)$$

where G = gas flux (lb/hr-ft^2).

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where G = gas flux (lb/hr-ft^2).

An air enthalpy versus water temperature plot, Figure 1, is convenient for a graphic description of the cooling theory. Wood and Betts[18] have thoroughly explained the plot. The equilibrium line represents the enthalpy of the saturated air surrounding each water droplet. The operating line is a result of the heat balance between the two phases and has a slope of L/G*. It is bounded by the inlet and outlet water temperatures and is fixed at point A by the enthalpy of the inlet air. The vertical distance between the equilibrium and operating lines represents the enthalpy driving force. By comparison with Equation (1), tower characteristic may be seen to be inversely related to the area ABCD of Figure 1.

Chen and Douglas have shown that backmixing is a significant mechanism of turbulent bed contacting. This deviation from countercurrent contacting is not accounted for in the above theory and undoubtedly causes uncertainty in the calculated tower characteristic. It is difficult to make corrections due to the lack of data available, thus the theory as presented is used as a first approximation in describing the cooling process. Also, no correction was made to account for the heat loss from the column.

The approach used in this study was one of parameter indentification through experimentation. The parameters were suggested in part by the theory. No a priori attempt was made to calculate column performance.

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*Assuming C_p=1.0 Btu/lb-°F for water, the true slope, C_pL/G, becomes L/G.

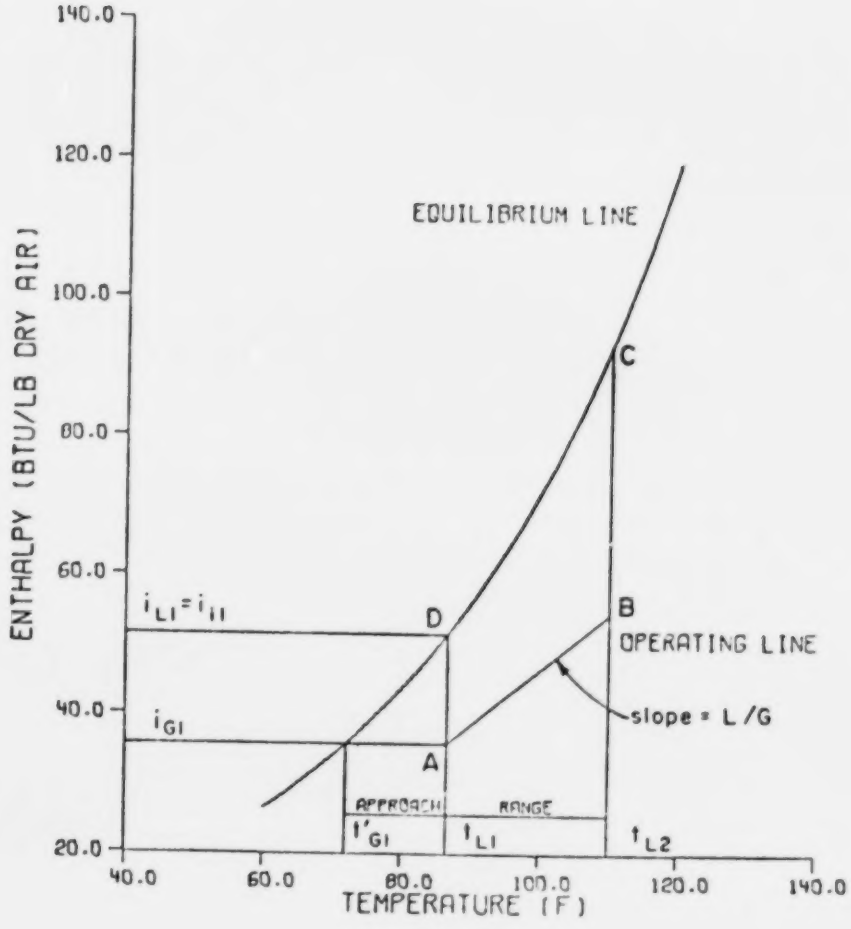

Figure 1. Air enthalpy versus water temperature.

SECTION IV

EQUIPMENT

Barile and Meyer have previously presented a description of the essential equipment used in this study.[13] Details of the equipment were published earlier.[12-16] The equipment can be considered in terms of the water system,the air system, and the column. A diagram of the process equipment is given in Figure 2. The main modification after Meyer[12], causing a significant improvement in operating characteristics, was the installation of curved vanes below the base plate to effect a gradual and uniform straightening of air before entering the column. As a result, uniform air flow was realized at the bed entrance thus preventing bulk packing rotation, channeling, and erroneous pressure drop data.

The water system consisted of a 646-liter (170 gal.) reservoir tank filled with tap water, a feed pump, bypass, heat source, feed lines, low and high range rotameters, 6 hose-type spray nozzles, a bottoms pump, and a return line emptying back into the reservoir. The heat was supplied by a wall mounted shell-and-tube heat exchanger using building steam. Heated water from the exchanger was returned to the reservoir and thoroughly mixed with the tank contents by the force of the water returning in the bypass line. The capacitance effect of the reservoir made hand control of the tower inlet hot water temperature quite easy.

The air system was made up of a muffler box, blower and motor, orifice metering device, and column feed line. Room air was used as the feed to the bottom of the column. The column, which consisted of a cylindrical plexiglass tube 0.29 m ID by 2.44 m in height, contained

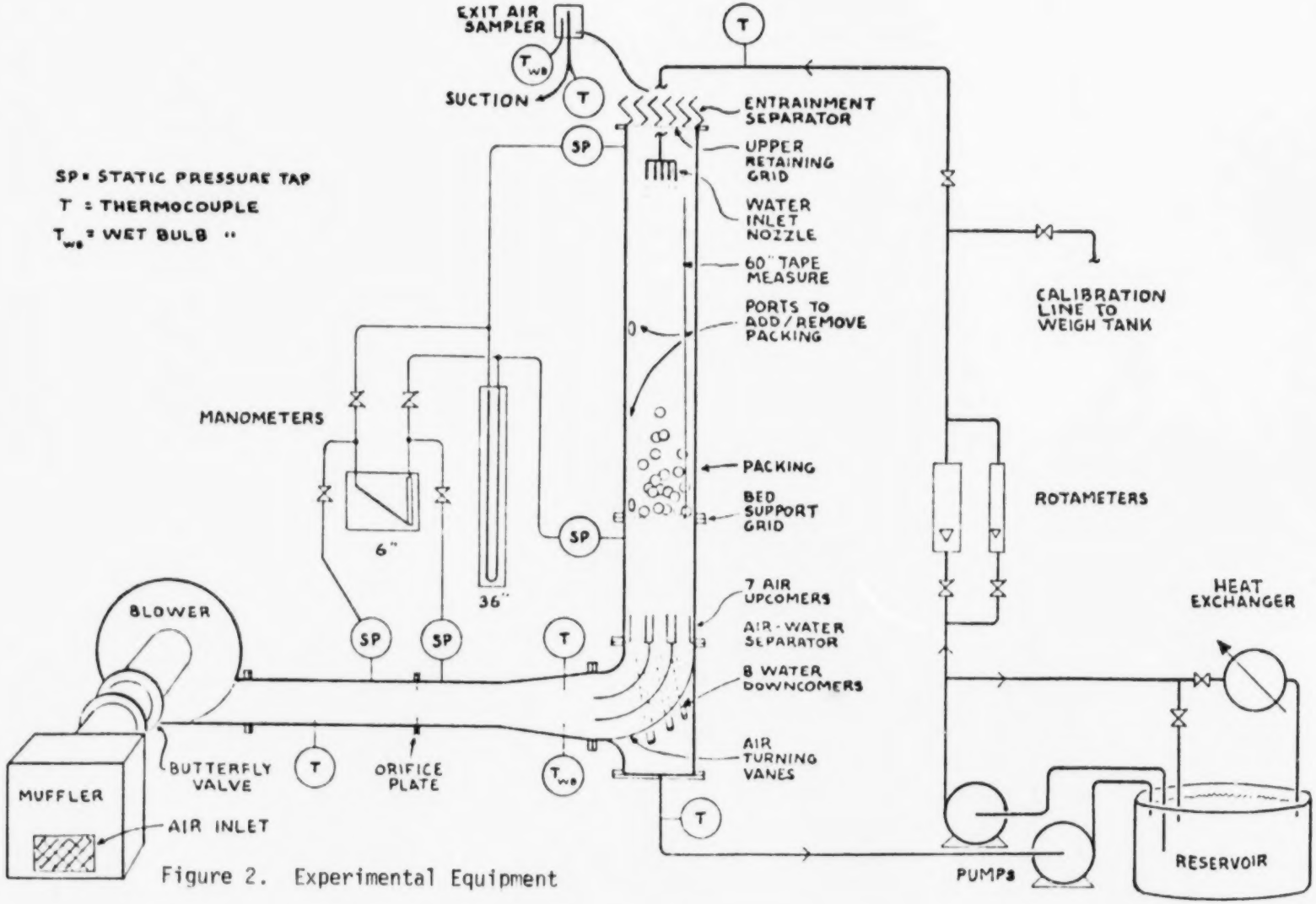

Figure 2. Experimental Equipment

the packing,a supporting grid for the packing, and a 0.3 m flow straightening section. At the base of the column was a 1.05 m. plenum chamber used to separate water and air streams.

The supporting grid for the packing was a 22-gauge, metal plate with 1.15-cm. square perforations on 1.27-cm straight centers. It was inserted into the column between the flanges connecting the column to the plenum chamber. It was purposely selected to have a high free-area, 82%, to "minimize" the effect of air pressure drop and water holdup at the grid.

A mist eliminator was set on the top of the column to prevent entrained water from escaping from the column. The eliminator was made of sheet metal and heavy screen. It provided a zig-zag path which entrapped most of the drift before it could escape from the column.

Hollow plastic spheres were used in the column as packing material. Two sizes of packing were used, 1.9 (polyethylene) and 3.8 cm (polypropylene) in diameter. Individually the spheres weighed 1.0 and 4.5 gm., and their bulk densities were 0.149 and 0.0961 gm./cc, respectively. Because of their low density the spheres were relatively easily fluidized. The spheres were purchased from Ac-Cello Products, Inc., New York, N.Y., at approximately $40.00/cu.ft.*

Measurements

Five process measurements were required as depicted in Figure 2.

1. Water and air dry bulb temperatures, inlet and outlet tower conditions: copper-constantan thermocouples with stainless steel sheathing.
2. Air wet-bulb temperatures, inlet and outlet: copper-

*In bulk, the price could be as low as $4.00/cu.ft., 1973 dollars.

constantan thermocouples with stainless steel sheathing covered with reservoir-fed wicks.

3. Water flow rate: rotameters
4. Air flow rate: orifice meter and inclined manometer (calibrated with pitot tube).
5. Air pressure drop in tower: water manometer, taps located just below the base plate and adjacent to the water spray nozzles. This measurement was corrected by subtracting from it the pressure drop measured in the same way without any packing in place and without water flowing. The correction, never greater than about 0.2 cm water, was calculated from the following:

   Pressure drop correction = $3.3 \times 10^{-9} G^2$, in. water, where G is measured in $lb/hr\text{-}ft^2$.

SECTION V

RESULTS AND DISCUSSION

The measured tower characteristics KaV/L are shown in Figure 3 for d_p = 3.8 cm and packing depth equal to or less than the pipe diameter. Three levels of flow are presented, i.e. L x G values, as well as the amount of cooling with no packing present. These data for d_p = 3.8 cm are presented instead of for d_p = 1.9 cm because of smaller pressure drop associated with the larger particles. A series of measurements for packing depths V_o > 30.5cm were omitted in this summary report due to their questionable use.

It is clear from Figure 3 that tower characteristics improve with increased packing depth, but the incremental improvement appears to diminish. Also, there is a consistent trend of higher KaV/L at lower flow levels.

In order to gain some idea of the relative performance of the turbulent bed contactor as a cooling device, comparisons are made with large Marley mechanical draft towers in terms of the same scaling parameter KaV/L calculated from basic data presented in a Marley report.[19] More discussion of this comparison will be given later.

A summary of the pertinent measured data on the turbulent bed contactor together with related calculations on Marley's towers are presented in Tables 1 and 2, respectively. Even though considerably more data were available from Dengler,[14] a limited selection was made with the objective of presenting as meaningful a comparison of the TBC

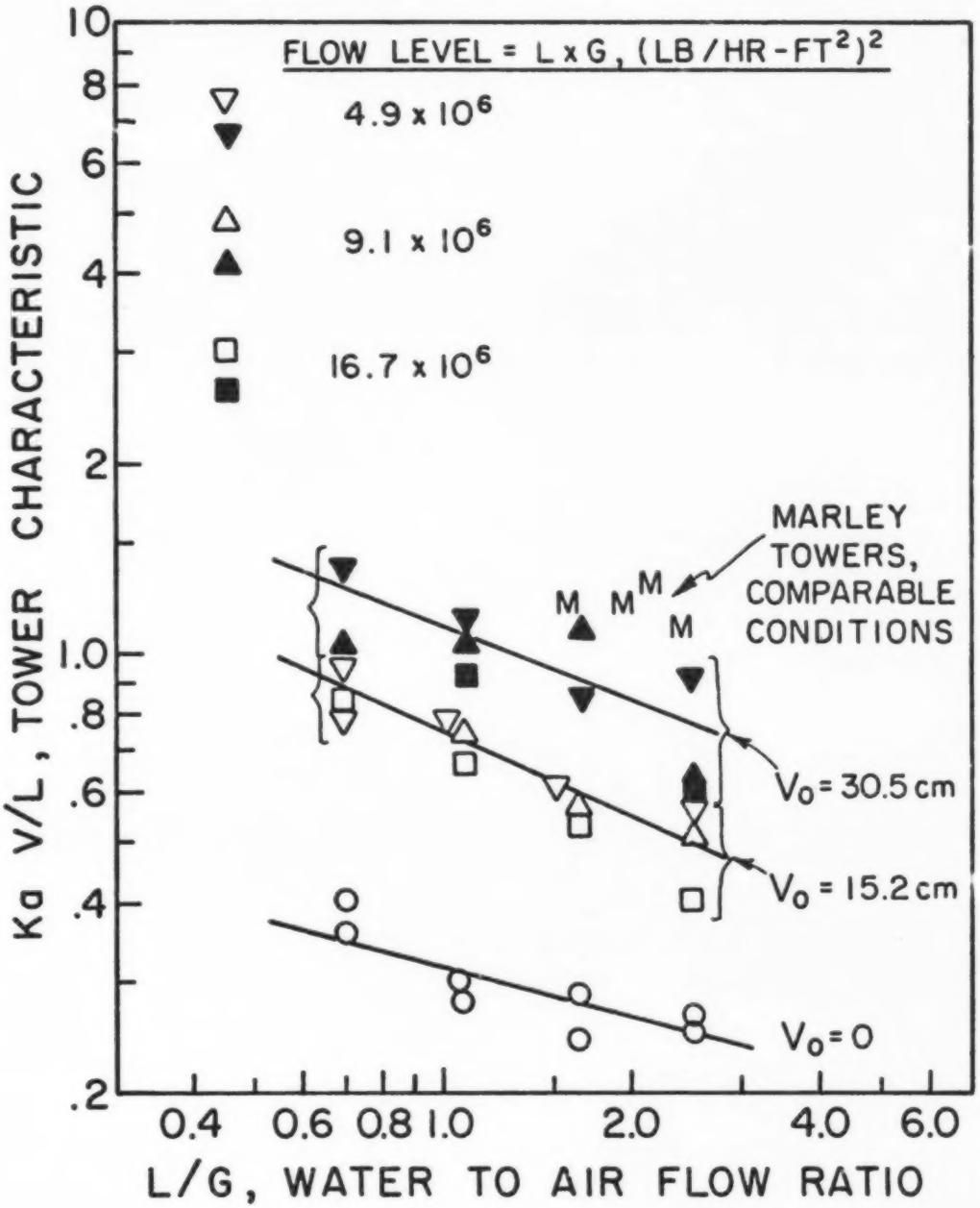

Figure 3. Tower characteristic vs. L/G.

TABLE 1. TBC PERFORMANCE AND CALCULATED PARAMETERS FOR 3.8-CM. PARTICLES

Run[a]	V_o,cm[b]	L/G	L,lb/hr-ft^2	Air flow, SCFM	ΔP_c, cm H_2O	Cooling range, °F	Air inlet wet bulb, °F	Inlet water, °F	Air inlet dry bulb, °F	KaV/L	Power ratio,%
350	15.2	0.70	1867	407	2.1	19.8	74.5	107.0	95.6	0.95	0.65
351	15.2	0.70	2515	552	2.3	18.2	74.4	107.0	94.3	0.79	0.76
352	15.2	0.70	3424	752	2.3	17.8	76.0	106.7	94.8	0.83	0.78
354	15.2	1.08	2292	326	2.3	13.2	82.1	106.2	103.0	0.74	0.74
355	15.2	1.08	3121	445	2.6	13.4	82.3	106.6	100.8	0.74	0.80
356	15.2	1.07	4224	603	2.9	12.6	82.6	106.0	99.2	0.67	0.94
358	15.2	1.65	2840	382	1.7	10.9	81.9	106.4	104.2	0.58	0.53
359	15.2	1.64	3863	361	2.4	11.0	81.2	106.0	102.0	0.58	0.68
360	15.2	1.64	5218	486	3.1	10.4	82.1	106.5	101.0	0.53	0.85
362	15.2	2.52	3503	213	1.9	10.0	79.9	106.2	108.2	0.57	0.36
363	15.2	2.52	4764	291	2.1	10.3	78.6	107.0	104.2	0.52	0.44
364	15.2	2.51	6472	396	2.9	9.5	75.2	106.1	100.0	0.40	0.66
378	15.2	2.52	3503	213	2.1	10.1	75.0	106.2	102.0	0.46	0.51

(Continued on next page)

a Dengler[14]

b Static packing height

TABLE 1. TBC PERFORMANCE AND CALCULATED PARAMETERS FOR 3.8-CM. PARTICLES (Continued)

Run[a]	V_o,cm[b]	L/G	L,lb/hr-ft^2	Air flow, SCFM	ΔP_c, cm H_2O	Cooling range, °F	Air inlet wet bulb, °F	Inlet water, °F	Air inlet dry bulb, °F	KaV/L	Power ratio,%
400	30.5	0.70	1874	408	4.1	20.8	77.0	106.0	96.2	1.35	1.60
401	30.5	0.70	2515	551	4.0	18.9	77.1	106.2	95.7	1.04	1.18
404	30.5	1.08	1874	408	4.2	20.8	79.0	106.7	106.0	1.11	0.90
405	30.5	1.08	3121	443	4.6	17.2	78.7	106.5	104.4	1.04	1.01
406	30.5	1.08	4224	601	4.9	15.8	79.1	106.1	103.3	0.91	1.16
408	30.5	1.66	2840	263	4.2	15.3	82.8	106.6	110.7	1.42	0.74
409	30.5	1.66	3863	357	4.7	14.2	82.0	106.3	107.3	1.09	0.87
410	30.5	1.65	5218	485	5.0	12.6	82.1	106.0	105.2	0.83	1.03
412	30.5	2.53	3503	212	4.1	11.9	79.7	105.9	108.3	0.91	0.67
413	30.5	2.52	4764	290	4.8	11.3	76.9	106.1	104.0	0.63	0.79
414	30.5	2.51	6472	395	5.2	11.5	75.8	106.3	100.5	0.61	0.83

a Dengler[14]

b Static packing height

TABLE 2. MARLEY MECHANICAL DRAFT TOWER [19]

	Characteristics and Power Ratio[a]					
Job #	L/G	Cooling range, °F	Air inlet wet bulb, °F	Inlet water, °F	KaV/L	Power ratio, %
10[b]	2.43	13.8	78.0	105.8	1.10	0.60
12	2.20	19.5	74.0	110.0	1.35	0.45
13[b]	2.15	12.8	76.0	100.8	1.30	0.71
17[b]	1.96	19.8	79.0	112.8	1.22	0.46
18[b]	1.60	20.8	78.0	111.3	1.19	0.47
25	1.91	21.6	75.0	106.6	3.15	0.86
28	1.94	15.5	70.0	100.5	1.40	0.58
29	1.21	21.0	66.0	101.3	1.40	0.51
30	1.76	19.3	62.0	101.3	1.33	0.47
31	1.71	18.0	66.2	100.4	1.50	0.56

a. Calculated from towers with flow greater than 150,000 gpm. [20]

b. Conditions are comparable with TBC runs, thus points are shown on Figure 3.

performance with mechanical draft tower performance as possible. Representative performance characteristics are presented to enable relative operating cost comparison of the TBC with mechanical draft towers. It is anticipated that the capital cost of TBC's will be smaller than conventional towers due to the smaller height of the TBC required to handle a given cooling load. However, no data can be produced at this time to justify this claim.

The entries in Tables 1 & 2 must be explained in order to gain understanding of the performance comparisons. In Table 1, the columns indicate the run number, the static packing depth, V_o, the tower characteristic, KaV/L, liquid to gas mass flow ratio, L/G, and the cooling load, all self explanatory. The corrected pressure drop ΔP_c does not include the wall effects of the tower as discussed earlier. This pressure drop was converted into equivalent thermal energy for delivering the air through the TBC. It is contained in the last column as the ratio of the total auxiliary power, i.e., the power delivered to the air and water, divided by the cooling load. The water pumping power was calculated for 4.6m water injection level for 85% efficiency. No fan efficiency was included, i.e. η_f was assumed 1.0. Therefore the auxiliary power is optimistically underestimated, a point not to be overlooked when comparing TBC data with Marley's. As a rough estimate of this difficiency, it should be noted that the water pumping power represented nearly 20-30% of the total auxiliary power. Therefore, the data can be adjusted accordingly when the fan efficiency becomes available. The power ratio is presented as a percentage level as the quantity of auxiliary power required to reject a unit power (thermal energy/time) as waste.

In Table 2 the tower characteristics were obtained from a numerical integration based on Marley's data of selected job number cases.[19] The fan BHP was used directly, and the water pumping power was calculated for 9.1 m injection height at 85% assumed pumping efficiency.

It is apparent from the comparisons of the power ratios presented in Table 1 to those in Table 2 that the TBC when taken at its best appears equal in performance to the mechanical draft towers. The majority of the data show that pressure drop per unit of cooling load through a TBC is twice that of mechanical draft towers. It must be mentioned that the mechanical draft towers of reference 19 were optimized as an integral part of a power generation system to produce power at least cost. Similar optimization of the TBC would result in a balanced performance vs. capital cost and might appear competitive despite the apparent performance disadvantage.

DISCUSSION

A primary concern in assessing the turbulent bed cooling tower is to compare it with acceptable towers already being used. Although there appears to be no parameter which reduces all variables to a common basis, the tower characteristic gives one widely recognized basis for comparison. Figure 3 demonstrates that industrial mechanical draft towers exhibit characteristics approximately 1.5 to 2 times as large as the TBC for one stage packing and 106°F inlet water temperature. However, note in Tables 1 and 2 that the comparison is more favorable for cases with similar inlet air wet bulb temperatures and inlet water temperature. Only the latter type cases are shown on this figure for Marley towers. Of course, the influence of both these temperatures are included in the tower characteristic but there appears to be some interaction of effects that is not eliminated by using tower characteristic. More questionable is the factor of V (bed height) in the characteristic since conventional vs. TBC towers would have fill or packing ratios of about forty to one. Thus, comparing tower characteristics may not be a critical variable for discriminating between grossly different tower designs but it is useful for crude screening.

A second parameter for comparison is introduced above*:

$$\text{POWER RATIO} = \frac{\text{(fan + water) power input}}{\text{cooling load}} \times 100$$

$$= \frac{\Delta P_c \; Q_{air}/\eta_f + Z \; g \; W_L/\eta_p}{W_L \; C_p \; \Delta T_L} \times 100$$

where

ΔP_c = corrected bed pressure drop

η_f = fan efficiency

Q_{air} = air flow, SCFM

ΔT_L = water cooling range

Z = water injection height

g = gravity acceleration

W_L = water mass rate

η_p = pump efficiency

C_p = water heat capacity

This ratio appears to be better than the tower characteristic in demonstrating a fair comparison between different towers, yet it does not distinguish between favorable and poor ambient conditions or differences in inlet-water temperature. Generally, low inlet-air wet bulb and high inlet-water temperatures cause tower performance to look good in terms of both tower characteristic and power ratio. However, for a case with similar inlet temperatures, the tower with a lower power ratio is desired if their capital costs are equal; or, the tower with lower capital cost is desired if their power ratios are equal. At this writing, it appears that the conventional mechanical draft tower, as represented by Marley case studies, is slightly more favorable in power ratio,and the TBC may be more favorable in capital cost. As noted

*Suggested by M. Shirazi, EPA project coordinator at Corvallis, Oregon.

above, further optimization of case studies would probably make the TBC appear more favorable. In addition, if there are any breakthroughs in reducing auxiliary air power in the TBC, this entire conclusion could change substantially. It is in this direction that further work is proceeding.

SECTION VI

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SECTION VII

GLOSSARY

Backmixing - Axial mixing of a fluid in the reverse direction relative to the bulk fluid direction.

Flooding - A condition in a vertical tower in which water can not pass down through the tower and begins to form a pool at the bottom.

Fluidized (Bed) - Solid particles, held in a column by a screen, which become suspended or mobile (as a liquid) due to air (friction) passing through the particles.

Height of a Transfer Unit - Defined by Equation (3), inversely proportional to good cooling performance.

Minimum Fluidizing Velocity - The air velocity which provides just enough friction to make a bed of particles become fluidized.

Number of Transfer Units - Defined by Equation (2), increasing as the tower load increases.

Plenum (Chamber) - Any section of a tower or column situated just below the packing or fill area. Usually air-water disengaging occurs here.

Slugging - A condition of flow within a fluidized bed where large portions of the packing (across the entire cross-section) move upward

together, i.e. non-random particle motion.

TBC - Turbulent bed contactor as applied to the task of cooling water.

SECTION VIII

APPENDIX

NEW RESULTS

At the time of this writing, new experiments are being performed which show improved performance in the TBC. Two stages of particles, separated by 0.81 m vertical space with each stage having 7.6 cm. (or 15.2 cm.) of 3.4 cm spheres, have exhibited substantially increased tower characteristics. Also, certain changes in the spheres appear to have lowered pressure drop by 10 to 20% while fractionally enlarging the cooling range. These results will be reported at a later date.